

CENOZOIC CALCAREOUS NANNOFOSSILS FROM THE PACIFIC OCEAN

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ABSTRACT.—The typical stratigraphic ranges of key Cenozoic calcareous nannofossil taxa in Pacific Ocean cores are presented. Two new genera and 16 new species from Pacific Ocean cores are described; these include: *Coccolithus magnicrassus*, *C. miopelagicus*, *Coccolithus? orangensis*, *Cyclicargolithus* n. gen., *Cyclolithella kariana*, *Discoaster bifax*, *D. intercalaris*, *D. loeblichii*, *D. neorectus*, *Fasciculithus clinatus*, *Helicopontosphaera heezenii*, *H. rhomba*, *Sphenolithus conicus*, *S. obtusus*, *S. spiniger*, *Striatococcolithus* n. gen., *Striatococcolithus pacificanus*, and *Triquetrorhabdulus milowii*.

INTRODUCTION

Calcareous nannofossils are microscopic calcite skeletal elements produced largely by Coccolithophyceae—marine, planktonic, one-celled, golden-brown algae. These 1-50 micron skeletal elements, composed of many still smaller calcite crystallites, have been preserved in marine strata since their earliest known occurrence in deposits of Early Jurassic age. Owing to their great abundance and evolutionary structural diversification, nannofossils can be used to subdivide marine strata into a sequence of biostratigraphic zones. The planktonic life-style of fossil nannoplankton in the light-penetrated and therefore current-influenced layer of the ocean ensured rapid dispersal of new forms. This factor contributes to the utility of nannofossils in transoceanic stratigraphic correlation.

Light microscopes set at magnifications of 250-1000 X and electron microscopes at 1000-20,000 X are used in the identification of nannofossils. For rapid comparison of many samples and for stratigraphic zonation utilizing assemblages, the light microscope is most convenient. For delineation of detailed surficial crystallite patterns that aid in phylogenetic and taxonomic studies, the electron microscope is useful. But the internal crystallographic orientation of the individual crystallites provides important distinctions for taxonomic discrimination, and this information comes only from cross-polarized light microscopy.

Approximately 3000 species of Cenozoic nannofossils have been described. The most important forms for zonation are the star-shaped discoasters, the placoliths (shaped like sewing-machine bobbins), and the cone-shaped sphenoliths (examples in Plate 1). Taxonomic distinctions within these groups are based for discoasters on the number and form of the rays and on accessory ornamentation of the rays and central area as seen in plan view; for placoliths on the crystallite crystallographic orientation, on relative proportions and circularity of the central area and rims of the upper and lower shields, and on any distinctive central-area ornamentation; for sphenoliths on the orientation of basal and apical spines as seen in cross-polarized light at various angles to the polarization.

ZONATION

The potential of calcareous nannofossils for biostratigraphic zonation was first indicated by Bramlette and Riedel (1954), and in 1967 the first general sequence of Cenozoic calcareous nannofossil zones was published (Bramlette and Wilcoxon, 1967; Hay et al., 1967). These zones were based on study of stratigraphic type stages in Europe, the Ciperó and Lengua Formations of Trinidad, long cored sequences from the JOIDES Blake Plateau drilling, and numerous short cores taken on oceanographic expeditions. This framework has provided useful guidelines for later studies based on the Deep Sea Drilling Project cores and on restudy of type-stage sections using the ranges of many newly described species. Recent studies furthering zonal refinement include: Gartner, 1969, 1971;

Bukry and Bramlette, 1970; Milow, 1970; Roth, 1970; Bukry, 1971; and Martini and Worsley, 1971. Because nannofossils are small and occur in vast numbers in a given sample, the whole assemblage can be scanned in a few minutes. Therefore, it is convenient to base zonal identifications on the character of the whole assemblage. Boundaries of zonal units (table 1) can usually be identified by closely spaced first and last occurrences of several species. Some of the key species used to recognize zone and subzone boundaries are indicated in tables 2 and 3. A full discussion of the character of these zonal units is given in the report on nannofossil stratigraphy for Deep Sea Drilling Project Leg 16 that explored the eastern equatorial Pacific Ocean (Bukry, in press).

NANNOFOSSIL DISSOLUTION

The diversity of species that compose nannoplankton assemblages is, to a large extent, controlled by selective dissolution of skeletal elements between the time of death in surface water and the time of final burial below the ocean bottom. Skeletal elements that bypass or survive ingestion by nannoplankton herbivores—microscopic, planktonic protozoans such as foraminifers and radiolarians (Tappan, 1971)—owing to their calcite composition are subjected to increased inorganic dissolution rates in progressively more calcite-undersaturated water at progressively greater ocean depth (Peterson, 1966). Although Berger (1970) has estimated that about four-fifths of the calcite supplied to the ocean floor is being redissolved, nannoplankton skeletons are more resistant to this effect than are other calcite microplankton skeletons. Part of their resistance to dissolution may be the result of incorporation of acid-resistant, fibrillar, cellulose-like polysaccharide material with the skeletal calcite (Franke and Brown, 1971). Chave and Suess (1967) have stated that organic coatings inhibit the precipitation of calcium carbonate on carbonate surfaces. Such coatings that inhibit carbonate-sea water interactions probably also retard dissolution of calcium carbonate particles in undersaturated water (Smith et al., 1968; Pytkowicz, 1969).

In addition to the possible organic coatings, variation in nannoplankton skeletal thickness relative to optic-axis orientation apparently accounts for some of the solution resistance of nannoplankton. Some of the most resistant taxa have a similar relation between the exposed surfaces and optic-axis orientation of their calcite crystallites. *Discoaster* and the upper shields of the placoliths *Coccolithus* and *Cyclcoccolithina* are typically the last remnants of a strongly dissolved fossil nannoplankton assemblage. In cross-polarized light, all of these appear dark because of the vertical orientation of the principal optic axis of their crystallites. Differences in dissolution rates along different crystallite axes, in conjunction with variation in crystallite thickness, could cause a significant range of structural differences to explain selective solution along taxonomic groupings.

The most diverse assemblages, those from warm-water areas that are little affected by calcite undersaturation, occur in deposits from the sublittoral shelf to the basal continental slope (approx. depths 50-2000 m). Such assemblages, which may contain common pentagonally-shaped *Braarudosphaera* or *Micrantholithus* (JOIDES Blake Plateau cores, for example), have been characterized as "nearshore" (Bramlette and Martini, 1964). As these nannoplankton are distinctively shaped, their general absence in deep-ocean (2000-6000 m) sediment is easy to determine. Indeed, some of these presumed nearshore indicator taxa have been reported in mid-ocean plankton and island samples, for example, *Braarudosphaera* in North Atlantic water (Hulburt, 1962; Hulburt and Rodman, 1963) and *Braarudosphaera* and *Micrantholithus* in shallow-water sediment from the Tonga Islands (Bramlette, 1970), suggesting that they are not restricted to inshore areas by envi-

ronmental factors while they are alive. Instead, these forms are probably poorly resistant to solution. Their spotty and far-flung distribution suggests that they are preserved in shallow (near-saturated) depositional areas and dissolved in deep (undersaturated) areas.

Table 1. Cenozoic calcareous nannoplankton zones and subzones. Approximate ages of series and subseries in million years from Berggren (1971).

SERIES OR SUBSERIES	AGE M. Y.	ZONE	SUBZONE
HOLOCENE	0.01	<i>Emiliania huxleyi</i>	
PLEISTOCENE	1.85	<i>Gephyrocapsa oceanica</i>	
		<i>Coccolithus doronicoides</i>	<i>Gephyrocapsa caribbeanica</i>
			<i>Emiliania annula</i>
UPPER PLIOCENE	3.7	<i>Discoaster browneri</i>	<i>Cyclococcolithina macintyreii</i>
			<i>Discoaster pentaradiatus</i>
			<i>Discoaster tamalis</i>
LOWER PLIOCENE	5.1	<i>Reticulofenestra pseudumbilica</i>	<i>Discoaster asymmetricus</i>
			<i>Sphenolithus neobabes</i>
			<i>Ceratolithus rugosus</i>
UPPER MIOCENE	10.5	<i>Ceratolithus tricorniculatus</i>	<i>Ceratolithus amplificus</i>
			<i>Triquetrorhabdulus rugosus</i>
		<i>Discoaster quinqueramus</i>	<i>Ceratolithus primus</i>
			<i>Discoaster berggrenii</i>
		<i>Discoaster neohamatus</i>	<i>Discoaster neorectus</i>
MIDDLE MIOCENE	14		<i>Discoaster bellus</i>
		<i>Discoaster hamatus</i>	
		<i>Catinaster coalitus</i>	
		<i>Discoaster exilis</i>	<i>Discoaster kugleri</i>
			<i>Coccolithus miopelagicus</i>
LOWER MIOCENE	22.5	<i>Sphenolithus heteromorphus</i>	
		<i>Helicopontosphaera ampliaperta</i>	
		<i>Sphenolithus belemnus</i>	
		<i>Triquetrorhabdulus carinatus</i>	<i>Discoaster druggii</i>
			<i>Discoaster deflandrei</i>
OLIGOCENE	38		<i>Dictyococcites abisectus</i>
		<i>Sphenolithus ciperoensis</i>	
		<i>Sphenolithus distentus</i>	
		<i>Sphenolithus predistentus</i>	
		<i>Helicopontosphaera reticulata</i>	<i>Cyclococcolithina formosa</i>
UPPER EOCENE	45		<i>Coccolithus subdistichus</i>
		<i>Discoaster barbadiensis</i>	<i>Cyclicargolithus reticulatus</i>
			<i>Discoaster tani tani</i>
MIDDLE EOCENE	53.5	<i>Reticulofenestra umbilica</i>	
		<i>Nannotetrina quadrata</i>	<i>Coccolithus staurion</i>
			<i>Chiasmolithus gigas</i>
			<i>Discoaster mirus</i>
		<i>Discoaster sublodoensis</i>	
LOWER EOCENE	65	<i>Discoasteroides kuepperi</i>	
		<i>Discoaster lodoensis</i>	
		<i>Tribrachiatus orthostylus</i>	
		<i>Discoaster diastypus</i>	
PALEOCENE	65	<i>Discoaster multiradiatus</i>	<i>Campylosphaera eodela</i>
			<i>Chiasmolithus bidens</i>
		<i>Discoaster nobilis</i>	
		<i>Discoaster mohleri</i>	
		<i>Heliolithus kleinpellii</i>	
		<i>Fasciculolithus tympaniformis</i>	
		<i>Cruciplacolithus tenuis</i>	

Comparison of fossil nannoplankton assemblages from Deep Sea Drilling Project cores taken from many ocean depths shows that the most solution-resistant genera—*Discoaster*, *Coccolithus*, *Cyclococcolithina*, *Reticulofenestra*, and *Dictyococcites*—occur in nearly all samples, shallow and deep. In fact, these taxa persist in some deep-ocean red-clay deposits after all other calcitic microfossils have been dissolved. On the contrary, such taxa as *Braarudosphaera*, *Micrantholithus*, *Transversopontis*, *Scyphosphaera*, and *Helicopontosphaera* are absent from red-clay deposits. By comparing many different coeval

Table 2. Typical ranges of some key late Cenozoic calcareous nannoplankton. Rare or sporadic occurrence dashed.

MIOCENE			PLIOCENE		PLEISTOCENE AND HOLOCENE		AGE
							COCCOLITH SPECIES
ZONE OR SUBZONE							
<i>E. huxleyi</i>							<i>Emiliana huxleyi</i>
<i>G. oceanica</i>							<i>Gephyrocapsa oceanica</i>
<i>G. caribbeanica</i>							<i>G. caribbeanica</i>
<i>E. annula</i>							<i>Ceratolithus cristatus</i>
<i>C. macintyreii</i>							<i>Cyclococcolithina macintyreii</i>
<i>D. pentaradiatus</i>							<i>Ceratolithus rugosus</i>
<i>D. tamalis</i>							<i>Discoaster browneri</i>
<i>D. asymmetricus</i>							<i>D. pentaradiatus</i>
<i>S. neobies</i>							<i>D. surculus</i>
<i>C. rugosus</i>							<i>D. asymmetricus</i>
<i>C. amplificus</i>							<i>D. tamalis</i>
<i>T. rugosus</i>							<i>D. variabilis decorus</i>
<i>C. primus</i>							<i>Reticulofenestra pseudumbilica</i>
<i>D. berggrenii</i>							<i>Sphenolithus neobies</i>
<i>D. neorectus</i>							<i>Ceratolithus tricorniculatus</i>
<i>D. bellus</i>							<i>C. amplificus</i>
<i>D. hamatus</i>							<i>C. primus</i>
<i>C. coalitus</i>							<i>Triquetrorhabdulus rugosus</i>
<i>D. kugleri</i>							<i>Discoaster quinqueramus</i>
<i>C. miopelagicus</i>							<i>D. berggrenii</i>
<i>S. heteromorphus</i>							<i>D. neorectus</i>
<i>H. ampliaperata</i>							<i>D. neohamatus</i>
<i>S. belemnos</i>							<i>D. bellus</i>
<i>D. druggii</i>							<i>D. hamatus</i>
<i>D. delalandei</i>							<i>Catinaster coalitus</i>
<i>D. abisectus</i>							<i>Discoaster exilis</i>
							<i>Discoaster kugleri</i>
							<i>Coccolithus miopelagicus</i>
							<i>Sphenolithus heteromorphus</i>
							<i>Cyclicargolithus floridanus</i>
							<i>Helicopontosphaera ampliaperata</i>
							<i>Sphenolithus belemnos</i>
							<i>Discoaster druggii</i>
							<i>Triquetrorhabdulus carinatus</i>
							<i>Dictyococcites abisectus</i>

assemblages, a general order of selective solution can be determined that reflects the relative depth of ancient ocean areas. The following list ranks lower Cenozoic nannofossil genera from those least common in deep-ocean sediment, at the beginning, to those most characteristic of very deep sediment at the end: *Transversopontis*, *Syracosphaera*, *Rhabdosphaera*, *Discolithina* [perforate], *Micrantholithus*, *Braarudosphaera*, *Lophodolitus*, *Scyphosphaera*, *Helicopontosphaera*, *Discolithina* [imperforate], *Sphenolithus*, *Chiasmolithus*, *Reticulofenestra*, *Dictyococcites*, *Cyclococcolithina*, *Coccolithus*, *Discoaster*.

Coeval samples from two nearby Pacific Ocean sites of greatly differing water depth are cited below as specific examples of taxonomically selective dissolution. Assemblages from the deep-water site of the pair are always less diverse. The species common to both the shallow site (DSDP 62: depth 2591 m, lat 1°52.2'N., long 141°56.0'E.) and the deep site (DSDP 63: depth 4472 m, lat 0°50.2'N., long 147°53.5'E.), are excluded, and the taxa listed below for each geologic subseries and zone are those solution-prone forms that oc-

Table 3. Typical ranges of some key early Cenozoic calcareous nannoplankton.

PALEOCENE	Eocene	OLIGOCENE	AGE OR ZONE OR SUBZONE	COCCOLITH SPECIES
<i>C. tenuis</i>				<i>Sphenolithus ciperoensis</i>
				<i>Dictyococcites abisectus</i>
				<i>Sphenolithus distentus</i>
				<i>Discoaster tani tani</i>
				<i>Sphenolithus predistentus</i>
				<i>Reticulofenestra umbilica</i>
				<i>Cyclococcolithina formosa</i>
				<i>Coccolithus subdistichus</i>
				<i>Cyclacargolithus reticulatus</i>
				<i>Discoaster barbadiensis</i>
				<i>Chiasmolithus grandis</i>
				<i>Coccolithus staurion</i>
				<i>Nannotetrina quadrata</i>
				<i>Chiasmolithus gigas</i>
				<i>Discoaster mirus</i>
				<i>D. subloboensis</i>
				<i>Rhabdosphaera inflata</i>
				<i>Coccolithus crassus</i>
				<i>Discoasteroides kuepperi</i>
				<i>Discoaster lodoensis</i>
				<i>Tribrachiatus orthostylus</i>
				<i>Discoaster diastypus</i>
				<i>Campylosphaera eodela</i>
				<i>Discoaster multiradiatus</i>
				<i>D. nobilis</i>
				<i>D. mohleri</i>
				<i>Chiasmolithus bidens</i>
				<i>Fasciculolithus tympaniformis</i>
				<i>Heliolithus kleinpellii</i>
				<i>Cruciplacolithus tenuis</i>



cur at the shallow site alone.

Lower Pleistocene *Coccolithus daronicoides* Zone:

Discoaster perplexus, *Helicopontosphaera sellii*, *Oolithotus antillarum*, *Rhabdosphaera clavigera*, *Umbilicosphaera mirabilis*.

Upper Pliocene *Discoaster brouweri* Zone:

Discoaster perplexus, *Helicopontosphaera sellii*, *Oolithotus antillarum*, *Scyphosphaera apsteinii*, *S. intermedia*, *Thoracosphaera* spp.

Lower Pliocene *Reticulofenestra pseudumbilica* Zone:

Discoaster perplexus, *Discolithina japonica*, *Helicopontosphaera kamptneri*, *H. sellii*, *Oolithotus antillarum*, *Scyphosphaera apsteinii*, *S. globulata*, *S. pulcherrima*, *Thoracosphaera* spp.

Upper Miocene *Discoaster quinqueramus* Zone:

Discoaster perplexus, *Discolithina japonica*, *Helicopontosphaera kamptneri*, *Scyphosphaera intermedia*, *Sphenolithus abies*, *Thoracosphaera* spp.

Middle Miocene *Discoaster hamatus* Zone:

Discoaster perplexus, *Helicopontosphaera kamptneri*, *Scyphosphaera* sp. cf. *S. pulcherrima*, *Sphenolithus abies*.

Establishing the relative order of nannofossil dissolution is important to provide information for interpreting the paleoecology of the assemblages (Douglas, 1971; Lawrence, 1971), and to improve precision in stratigraphic zonation.

SYSTEMATIC PALEONTOLOGY

Genus *Coccolithus* Schwarz, 1894

Coccolithus magnicrassus n. sp.

Pl. 2, figs. 1-5

Description.—This large, elliptic placolith is characterized by a small central area and a broad finely striate rim. In light-microscope examination, the central area is prominent and the rim faint, being at high and low relief with respect to the mounting medium ($n = 1.518$). In cross-polarized light the central area is bright, forming a small elliptic collar around an elliptic central opening; whereas the rim is faint, with diffused strongly curving extinction bands. The upper rim has 55-80 radial crystallites, and is distinctly larger than the lower rim.

Remarks.—*Coccolithus magnicrassus* is distinguished from other similar placoliths by the combined characters of (1) large overall size; (2) small, high relief central area with simple central opening; (3) broad upper rim, composed of many elements, that is only moderately bright in cross-polarized light and has diffuse, strongly curving extinction bands. *Toweius craticulus* Hay and Mohler is smaller with a narrower rim; *Reticulofenestra hillae* Bukry and Percival has a larger central opening and in cross-polarized light a fully bright rim with broader less curved extinction bands; *Coccolithus crassus* Bramlette and Sullivan is distinctly smaller, and the upper, larger rim is dark in cross-polarized light. A comparison of *C. crassus* with *C. magnicrassus* is shown in Pl. 2, fig. 2.

Plate 1. Electronmicrographs of carbon-platinum replicas showing surface crystallite patterns of some typical forms of Cenozoic calcareous nannofossils. 1. *Syracosphaera pulchra* Lohmann, Pleistocene, Shatsky Rise, DSDP 47.0-1-4, 77-78 cm. 11,000 X. 2. *Helicopontosphaera kamptneri* Hay and Mohler, Pleistocene, Shatsky Rise, DSDP 47.0-1-4, 77-78 cm. 7,000 X. Diatom fragment at lower right corner. 3. *Rhabdosphaera clavigera* Murray and Blackman, Pleistocene, Shatsky Rise, DSDP 47.0-1-4, 77-78 cm. 8,000 X. 4. Group of placoliths and discoasters, Pliocene, Caroline Ridge, DSDP 57.2-1-6, 0-3 cm. 1,700 X. 5. Group of placoliths and a discoaster, Miocene, Caroline Ridge, DSDP 55.0-11-5, 78-80 cm. 4,000 X. 6. Group with placolith, discoaster, and sphenolith, Eocene, Horizon Ridge, DSDP 44.0-3-5, 145-150 cm. 3,000 X.

Occurrence.—*Coccolithus magnicrassus* occurs in lower Eocene marine sediment cored in the North Pacific and North Atlantic Ocean and in the Donzacq Marl of France. It does not range as high as *C. crassus*, for it is recognized only from the *Discoaster lo-doensis* Zone thus far.

Size.—16-20 microns.

Holotype.—USNM 176883 (Pl. 2, figs. 1-2).

Paratype.—USNM 176884-176886.

Type locality.—DSDP 47.2-7-3, 104-105 cm, Shatsky Rise, northwestern Pacific Ocean.

Coccolithus miopelagicus n. sp.

Pl. 2, figs. 6-9

Description.—This large placolith has a medium-sized central area and a broad distinctly striate rim. In light-microscope examination, both the rim and central area are prominent. In cross-polarized light the central area is bright with distinct extinction bands; the lower (smaller) rim is bright, but the upper rim is dark. A small simple elliptical opening or slit in the central area is aligned with the long axis of the placolith.

Remarks.—The similarly constructed species, *Coccolithus eopelagicus* (Bramlette and Riedel) is distinguished from *Coccolithus miopelagicus* by several criteria: (1) Rim counts for *C. eopelagicus* are higher, 50 to 61 instead of 40 to 49; (2) Measurement of ten typical specimens shows that the central area of *C. eopelagicus* occupies a greater percentage of the long axis, 59 ± 1 percent instead of 50 ± 5 percent; (3) The central area also occupies a greater percentage of the short axis, 49 ± 2 percent instead of 42 ± 3 percent. The general distinction of *C. miopelagicus* from *C. eopelagicus* and large specimens of the younger *C. pelagicus* (Wallich) s.s. is the distinctly smaller central area of *C. miopelagicus* with respect to the rim area. Large specimens of *C. miopelagicus* are 20 microns in major axis length, but as indicated by Bramlette and Riedel (1954) these middle Tertiary forms, similar to *C. eopelagicus*, are generally smaller.

Occurrence.—*Coccolithus miopelagicus* is most common in lower and middle Miocene sediment from the Atlantic and Pacific Oceans and Caribbean Sea. The appearance of *C. miopelagicus* populations near the Oligocene-Miocene boundary is probably a gradual transition from *C. eopelagicus* resulting from increasing temperatures. Some tropical middle Eocene *C. eopelagicus* populations have a fair percentage of associated *C. sp. cf. C. miopelagicus*, whereas lower Oligocene (cooler temperatures) and high latitude middle Eocene assemblages contain only *C. eopelagicus*. The disappearance of *C. miopelagicus* at the *Catinaster coalitus* Zone is abrupt.

Size.—13 to 18 microns.

Holotype.—USNM 176888 (Pl. 2, figs. 7-8).

Paratype.—USNM 176887, 176889.

Type locality.—DSDP 63.0-3-4, 80-81 cm, East Caroline Basin, western equatorial Pacific Ocean.

Plate 2. Photomicrographs: 2,000 X. 1-5. *Coccolithus magnicrassus*, n. sp. (1) holotype USNM 176883, DSDP 47.2-7-3, 104-105 cm; (2) holotype at left, *Coccolithus crassus* Bramlette and Sullivan at right, cross-polarized, (3) USNM 176884, (4) USNM 176885, cross-polarized, (5) USNM 176886, DSDP 47.2-7-2, 100-101 cm, cross-polarized. 6-9. *Coccolithus miopelagicus*, n. sp. (6) USNM 176887, DSDP 63.1-8-3, 80-81 cm, (7) holotype USNM 176888, DSDP 63.0-3-4, 80-81 cm, (8) holotype, cross-polarized, (9) USNM 176889, DSDP 70.0-3-3, 63-64 cm. 10-11. *Coccolithus? orangensis*, n. sp. (10) holotype USNM 176890, DSDP 55.0-13-1, 120-121 cm, (11) holotype, cross-polarized; three small *Cyclicargolithus sp. cf. C. floridanus* (Roth and Hay) with straight extinction lines are present below the holotype.



***Coccolithus? orangensis* n. sp.**

Pl. 2, fig. 10; Pl. 3, figs. 1-3

Description.—This small elliptic placolith has exceptionally high relief with respect to the mounting medium ($n = 1.518$). Individual crystallites are not discernible by light microscope. In cross-polarized light, the coccolith is bright except for a small central opening. The extinction bands are strongly curved and become abruptly diffused in a narrow margin at the outer perimeter that is slightly brighter than the rest of the nannofossil.

Remarks.—*Coccolithus? orangensis* is not readily assignable to any presently described genus. What might be a side view of this species is shown at the right side of figure 1-2 of Plate 3. The exceptionally high relief, characteristically exceeding that of discoasters, small size, and bright perimeter help to distinguish *C.? orangensis* from other elliptic nannofossils. There appears to be a narrow, high relief collar structure around the small central opening, resulting in a ring-like depression between the perimeter and collar. *C.? orangensis* is distinguished from *Cyclicargolithus floridanus* (Roth and Hay) by its elliptic outline, high relief, and bright perimeter.

Occurrence.—*Coccolithus? orangensis* is never abundant but is a consistent low-frequency member of upper Oligocene and lower Miocene assemblages assigned to the *Sphenolithus ciperensis* Zone and *Triquetrorhabdulus carinatus* Zone. It occurs in both Pacific and Atlantic Ocean deep-sea cores.

Size.—4 to 6 microns.

Holotype.—USNM 176890 (Pl. 2, figs. 10-11).

Paratypes.—USNM 176891-176892.

Type locality.—DSDP 55.0-13-1, 120-121 cm, Caroline Rise, western equatorial Pacific Ocean.

***Cyclicargolithus* n. gen.**

Description.—Circular to subcircular placoliths constructed of two shields connected by a central tube that may be closed or open. In plan view, the upper shield is bright in cross-polarized light.

Type species.—*Coccolithus floridanus* Roth and Hay in Hay and others, 1967, Gulf Coast Assoc. Geol. Soc. Trans., v. 17, p. 455, Pl. 6, figs. 1-4.

Remarks.—The genus *Cyclococcolithina* Wilcoxon (1970) included circular to subcircular forms of two kinds—those with dark upper shields and those with bright upper shields when viewed in cross-polarized light. The significant difference in the orientation of the optic axis of the shield crystallites that accounts for this distinction is considered to be of generic rank. Therefore *Cyclococcolithina* Wilcoxon is herein restricted to those forms having dark upper shields such as *Cyclococcolithina formosa* and the type species *Cyclococcolithina leptopora*. Forms with bright upper shields are transferred to *Cyclicargolithus*. The circular to subcircular outline of this genus distinguishes it from elliptical *Coccolithus* Schwarz, which has a dark upper shield in cross-polarized light.

***Cyclicargolithus floridanus* (Roth and Hay) n. comb.**

Coccolithus floridanus Roth and Hay in Hay and others, 1967, Gulf Coast Assoc. Geol. Soc. Trans. 17: 455, Pl. 6, figs. 1-4.

Cyclococcolithus neogammatum Bramlette and Wilcoxon, 1967, Tulane Studies Geol. 5: 104, Pl. 1, figs. 1-3; Pl. 4, figs. 3-5.

Cyclococcolithus floridanus (Roth and Hay), of Müller, 1970, Geologica Bavarica 63: 113, Pl. 2, figs. 1-3.

Cyclococcolithus floridanus (Roth and Hay), of Roth, 1970, Eclogae Geol. Helv. 63: 854, Pl. 5, fig. 6.

Remarks.—The original definition of *Coccolithus floridanus* Roth and Hay describes a small (3.6 to 5 micron) elliptic placolith. The original definition of *Cyclococcolithus neo-*

*gamma*tion Bramlette and Wilcoxon describes a medium sized (6 to 12 micron) circular placolith. According to Roth (1970) the electronmicrograph paratypes of these two species show the same construction and number of rim elements. The slight difference in size and shape noted in the written descriptions probably resulted from the description of end members of the same species and from the use of different instrumentation.

Cyclicargolithus luminis (Sullivan) n. comb.

Cyclococcolithus luminis Sullivan, 1965, Univ. Calif. Publ. Geol. Sci. 53: 33, Pl. 3, figs. 9a, b.

Cyclicargolithus reticulatus (Gartner and Smith) n. comb.

Cyclococcolithus reticulatus Gartner and Smith, 1967, Univ. Kansas Paleont. Contr., Paper 20, p. 4, Pl. 5, figs. 1-4.

Genus *Cyclolithella* Loeblich and Tappan, 1963

Cyclolithella kariana n. sp.

Pl. 3, figs. 4-5

Description.—This small circular coccolith has a small circular central opening that occupies about a quarter to a third of the diameter. The thick upper shield is composed of about 12 to 20 curving crystallites that are strongly imbricated, indicated by the spiralling effect as focus is raised or lowered through the coccolith. The margin of the central opening and outer perimeter is generally smooth, but the perimeters of a few etched(?) specimens appear slightly scalloped. In cross-polarized light, no sharp black extinction bands are seen; instead, four light-gray rays each occupy two or three crystallites.

Remarks.—*Cyclolithella kariana* is distinguished from other species of *Cyclolithella* by the small central opening. It is further distinguished from the most similar species, *Cyclolithella pactilis* Bukry and Percival, by curved, gray extinction bands instead of straight black ones, when viewed in cross-polarized light.

Occurrence.—*Cyclolithella kariana* occurs commonly in lower Eocene sediment assigned to the *Discoaster lodoensis* Zone at DSDP 47.2 on the Shatsky Rise of the northwestern Pacific Ocean.

Size.—6 to 9 microns.

Holotype.—USNM 176893 (Pl. 3, figs. 4-5).

Type locality.—DSDP 47.2-7-3, 104-105 cm, Shatsky Rise, northwestern Pacific Ocean.

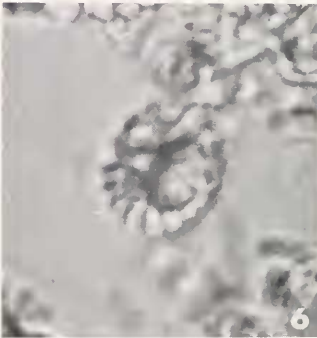
Genus *Discoaster* Tan, 1927

Discoaster bifax n. sp.

Pl. 3, figs. 6-11

Description.—This small species is constructed of 10 to 15 (typically 14) approximately radial rays that are appressed and terminate in broad points. High central stems extend from each side of the discoaster. The stem on one side is slender, occupying only 25 percent of the shield diameter, whereas the stem on the other side is consistently twice as wide, occupying 50 percent of the shield diameter. No birefringence is seen in cross-polarized light.

Remarks.—*Discoaster bifax* is distinguished from other compact discoasters, *Discoaster barbadiensis* Tan, *D. circularis* Hoffmann, *D. multiradiatus* Bramlette and Riedel, *D. saipanensis* Bramlette and Riedel, and *D. salisburgensis* Stradner, by tall central stems



on both sides of the discoaster shield instead of only on one side. It is distinguished from other double-stemmed forms such as *D. diastypus* Bramlette and Sullivan and *D. bollii* Martini and Bramlette by stems of strongly contrasting width on opposite sides of the same specimen.

Occurrence.—*Discoaster bifax* occurs commonly in Stetson 21 at 147-152 cm from the Atlantic Ocean. Associated nannofossils in this sample such as *Chiasmolithus grandis* (Bramlette and Riedel) and *Reticulofenestra umbilica* (Levin) indicate a middle Eocene age. *D. bifax* is sparse in coeval Pacific Ocean sediment from the *Reticulofenestra umbilica* Zone of the East Pacific Rise, DSDP 74.0-12-3, 24-25 cm.

Size.—5 to 10 microns.

Holotype.—USNM 176895 (Pl. 3, figs. 7-8).

Paratypes.—USNM 176894, 176896-176897.

Type locality: Stetson 21, 147-152 cm, northwestern Atlantic Ocean.

***Discoaster intercalaris* n. sp.**

Pl. 3, fig. 12; Pl. 4, figs. 1-2

Discoaster brouweri Tan. of Stradner and Papp, 1961, (*partim*), Jahrb. Geol. Bundesanst. [Wien], v. 7, p. 85, Pl. 20, fig. 6.

Description.—This medium-sized, six-rayed species has a large central area and a central stem. The symmetric radially arrayed rays show a distinct tapering and terminate in simple rounded points. Some specimens have a small indentation at the tip.

Remarks.—*Discoaster intercalaris* is a simple form that is distinguished from the *Discoaster variabilis* group by a single-pointed termination of the rays instead of a broadly flaring bifurcation. It is distinguished from *Discoaster brouweri brouweri* Tan, emended, by the wide central area and marked taper of the rays. It is distinguished from *Discoaster neorectus* Bukry by its smaller size and the straight to slightly concave sides of the rays.

Occurrence.—*Discoaster intercalaris* is common in upper Miocene to upper Pliocene marine sediment cored by the Deep Sea Drilling Project during Leg 5 at sites off northern California. The cool-water aspect of the associated nannofossil assemblages and the similarity in form of *D. intercalaris* and *D. variabilis variabilis* suggest that *D. intercalaris* may be a cool-water relative of *D. variabilis variabilis* that failed to develop bifurcations. This possibility is indicated by the small size of the bifurcations of *D. variabilis variabilis* specimens associated with *D. intercalaris*. More southerly populations of *D. variabilis variabilis* have larger, more robust terminations (see Martini and Bramlette, 1963, Pl. 104, figs. 4-8).

Size.—10 to 16 microns.

Holotype.—USNM 176899 (Pl. 4, fig. 1).

Paratypes.—USNM 176898, 176900.

Type locality.—DSDP 36-12-5, 77-78 cm, western flank of Gorda Rise, northeastern Pacific Ocean.

***Discoaster loeblichii* n. sp.**

Pl. 4, figs. 3-5

Plate 3. Photomicrographs: 2,000 X. 1-3. *Coccolithus? orangensis* n. sp. (1) USNM 176891, DSDP 74.0-4-4, 63-64 cm, cross-polarized, plan view on left, (2) same, bright field, (3) USNM 176892, DSDP 77B-37-4, 65-66 cm, cross-polarized. 4-5. *Cyclolithella kariana* n. sp. (4) holotype USNM 176893, DSDP 47.2-7-3, 104-105 cm, (5) holotype, cross-polarized. 6-11. *Discoaster bifax* n. sp. (6) USNM 176894, STETSON 21, 147-152 cm, tilted, (7) holotype USNM 176895, high focus, (8) holotype, low focus, (9) USNM 176896, tilted, (10) USNM 176897, high focus, (11) same, low focus. 12. *Discoaster intercalaris* n. sp. (12) USNM 176898, DSDP 36-12-5, 77-78 cm.

Description.—This small- to medium-sized, six-rayed species has a central area occupying about a third of the total discoaster diameter. It has a small central knob, and the rays are distinctly tapered, being widest near the central area. The tips of the rays have distinctive unequal bifurcations that are bent slightly out of the plane of the rays. Both limbs of the bifurcation taper to points, but all six sets show one limb that is consistently more than twice as long as the other. The sense of direction of the resulting asymmetric bifurcation is always the same for all six rays of a given specimen.

Remarks.—Besides *Discoaster loeblichii*, the only other six-rayed discoaster with ordered, therefore primary, crescent-forming bifurcations is *Discoaster calcaris* Gartner, which is a large form more comparable in size, proportions, and occurrence to five-rayed *D. hamatus* Martini and Bramlette. *Discoaster loeblichii* is distinguished by a proportionally larger central area, by shorter, broader, and more tapering rays, and by a smaller average size (12 to 16 microns instead of 16 to 22 microns). It appears to have been derived from the *Discoaster variabilis* group, and differs from *D. variabilis variabilis* Martini and Bramlette by the unequal bifurcations that form an asymmetric crescent at the ray tips.

Occurrence.—*Discoaster loeblichii* was a limited stratigraphic range in the early late Miocene *Discoaster neohamatus* Zone, where it is most common in the middle to upper part of that zone. Geographically, *D. loeblichii* is known from the tropical Pacific Ocean areas cored during Deep Sea Drilling Project Legs 7 to 9.

Size.—11 to 16 microns.

Holotype.—USNM 176902 (Pl. 4, fig. 4).

Paratype.—USNM 176901, 176903.

Type locality.—DSDP 83A-15-6, 130-131 cm, Panama Basin, eastern equatorial Pacific Ocean.

***Discoaster neorectus* n. sp.**

Pl. 4, figs. 6-7

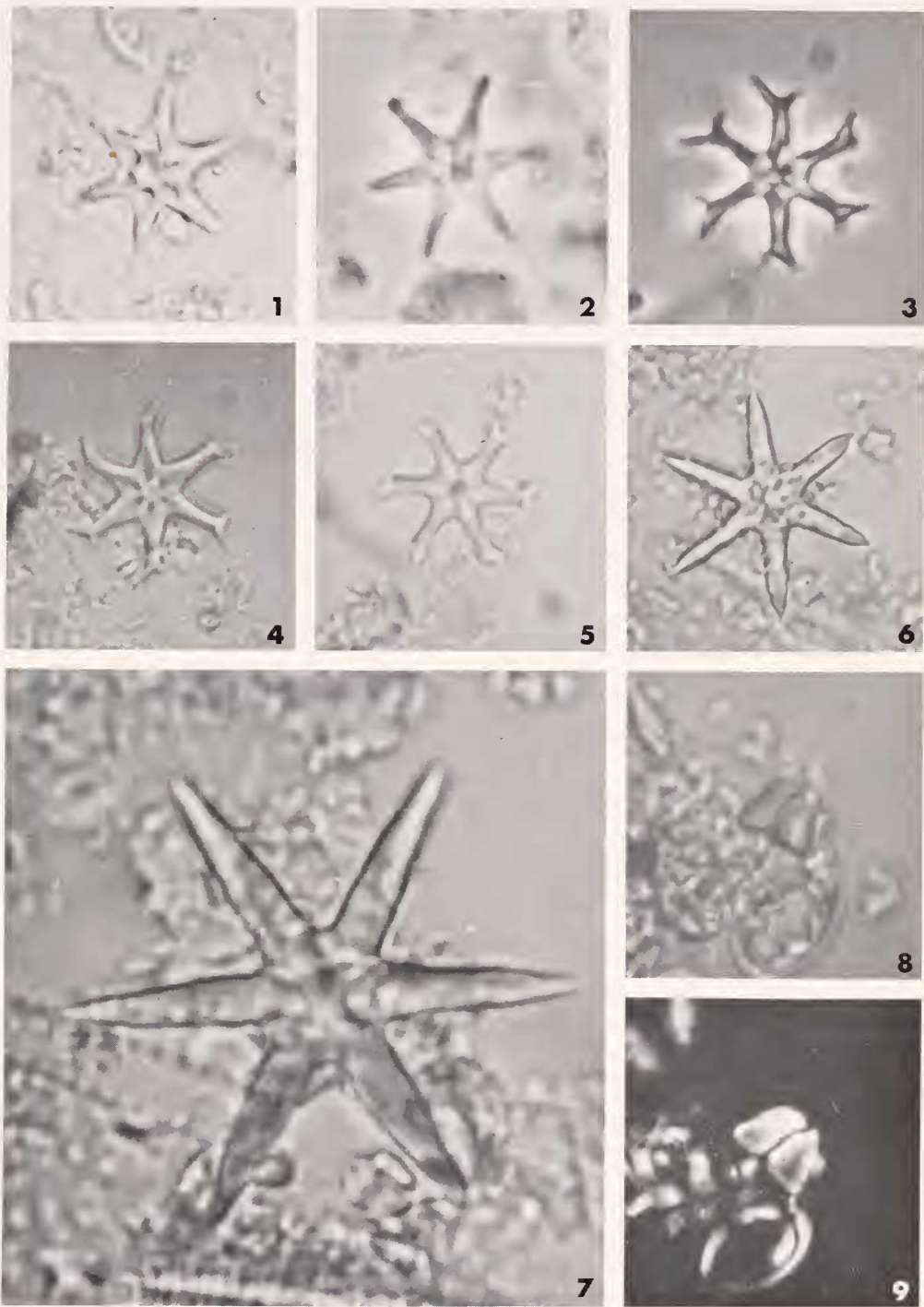
Description.—This gigantic six-rayed species has a small central stem but no separately marked central area. The rays are long and symmetrically arranged, with sides that are straight or slightly convex. The rays have a slight taper and terminate in simple sharp points.

Remarks.—*Discoaster neorectus* has simple, pointed terminations that distinguish it from *Discoaster brouweri brouweri* Tan, emended, which has rays bent like umbrella ribs, and *D. brouweri rutellus* Gartner, which has blade-like wedges at the end of each ray. *Discoaster neorectus* is distinguished from *D. intercalaris* by the narrower taper of the rays and by the lack of a significant central area.

Occurrence.—In nannofossil assemblages from the Pacific Ocean, *Discoaster neorectus* is common in only a limited stratigraphic horizon of the upper Miocene, upper *Discoaster neohamatus* Zone to lower *Discoaster quinqueramus* Zone. The unusually large size of this species makes it a convenient guide. Slightly less robust specimens than those of the Pacific, but equally large, are common in Core DSDP 3-10 from the Gulf of Mexico.

Size.—20 to 38 microns.

Plate 4. Photomicrographs: 2,000 X, unless noted otherwise. 1-2. *Discoaster intercalaris* n. sp. (1) holotype USNM 176899, DSDP 36-12-5, 77-78 cm, (2) USNM 176900. 3-5. *Discoaster loeblichii* n. sp. (3) USNM 176901, DSDP 83A-16-4, 64-65 cm, (4) holotype USNM 176902, DSDP 83A-15-6, 130-131 cm, (5) USNM 176903, DSDP 83A-16-4, 64-65 cm. 6-7. *Discoaster neorectus* n. sp. (6) USNM 176904, DSDP 72.0-3-4, 63-64 cm, magnification 1,000 X, (7) holotype USNM 176905. 8-9. *Fasciculithus clinatus* n. sp. (8) holotype USNM 176906, DSDP 47.2-9-5, 77-78 cm. (9) holotype, cross-polarized.



Holotype.—USNM 176905 (Pl. 4, fig. 7).

Paratype.—USNM 176904.

Type locality.—DSDP 72.0-3-4, 63-64 cm, western flank East Pacific Rise, equatorial Pacific Ocean.

Genus *Fasciculithus* Bramlette and Sullivan, 1961

***Fasciculithus clinatus* n. sp.**

Pl. 4, figs. 8-9

Description.—This small simple species has a short conical form with a slightly rounded top that produces an almost triangular outline in side view. The base line is essentially straight in side view and is slightly longer than the upper sides, which are straight to slightly convex. In cross-polarized light, a single median extinction band bisects the triangular outline.

Remarks.—*Fasciculithus clinatus* is distinguished from other species of *Fasciculithus* by its small size and almost triangular outline. The only comparable small form, *F. tympaniformis* Hay and Mohler, is cylindric, with parallel instead of inclined sides. *Fasciculithus magnus* Bukry and Percival may have inclined sides for only half of its height and is much larger than *F. clinatus*. Also, *F. clinatus* lacks the pit-and-ridge ornamentation developed in several other species, such as *F. involutus* Bramlette and Sullivan.

Occurrence.—*Fasciculithus clinatus* is common in upper Paleocene sediment of the Shatsky Rise in the northwestern Pacific Ocean.

Size.—height, 4 to 6 microns.

Holotype.—USNM 176906 (Pl. 4, figs. 8-9).

Type locality.—DSDP 47.2-9-5, 77-78 cm, Shatsky Rise, northwestern Pacific Ocean.

Genus *Helicopontosphaera* Hay and Mohler, 1967

***Helicopontosphaera heezenii* n. sp.**

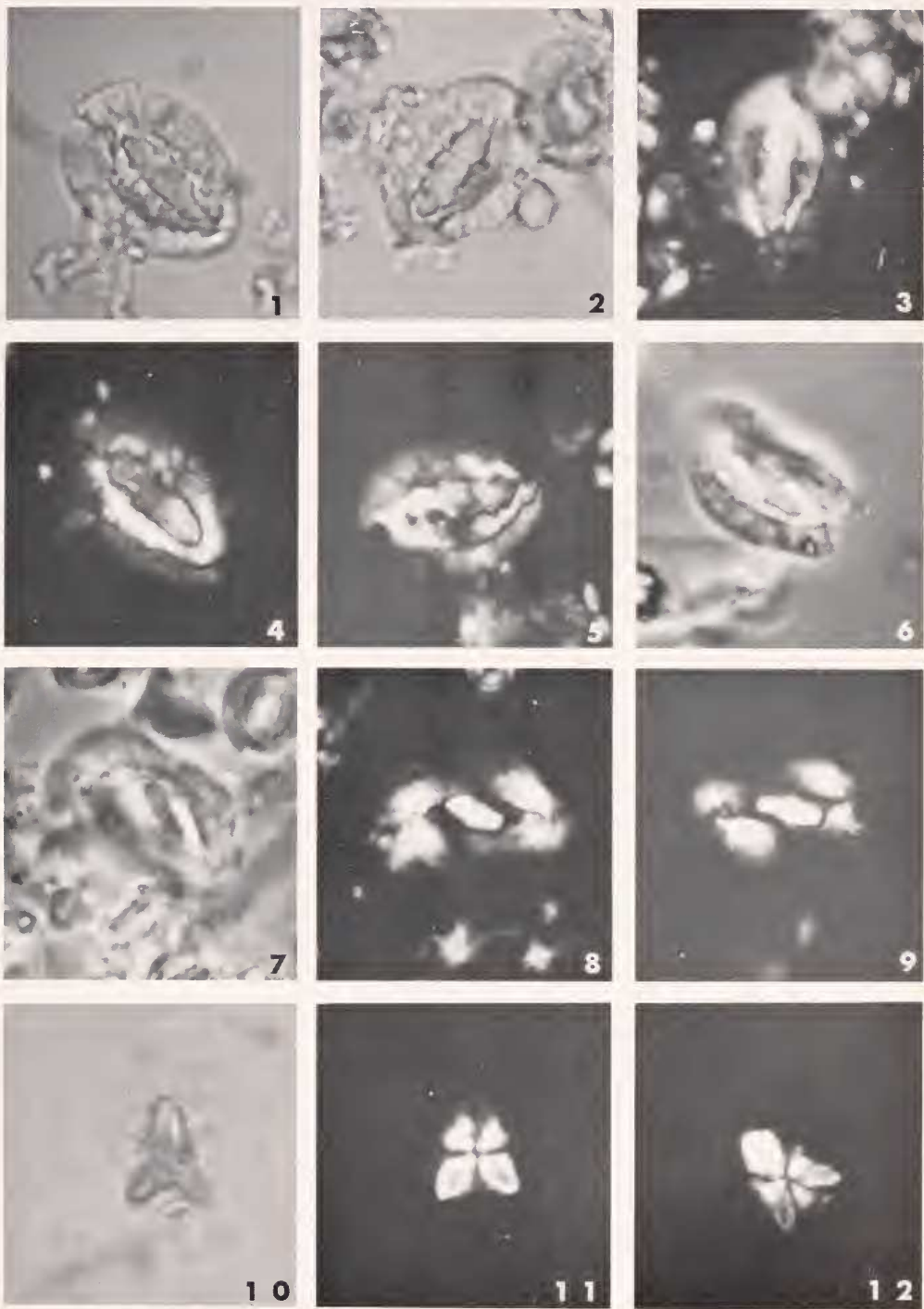
Pl. 5, figs. 1-5

Description.—This large species has a long bar, aligned with the long axis of the nanofossil, that dominates the central area. The length of the bar is 53 to 61 percent of the total nanofossil length. The bar is rounded at the ends, and although the sides are normally smooth, some etched specimens show irregularities suggesting small perforations. In cross-polarized light, the central bar is brightest when aligned with a polarization direction.

Remarks.—*Helicopontosphaera heezenii* is distinguished from similar forms such as *Helicopontosphaera lophota* (Bramlette and Sullivan) and *H. papillata* Bukry and Bramlette by the greater length and the axial alignment of the central bar. It is distinguished from *H. reticulata* (Bramlette and Wilcoxon) by its non-rhomboid shape and non-diagonal central bar.

Occurrence.—*Helicopontosphaera heezenii* is common in the upper middle Eocene at DSDP 44 on Horizon Ridge in the northwestern Pacific Ocean, where it was first recognized. It also occurs in coeval sediment of Stetson 21, northwestern Atlantic Ocean.

Plate 5. Photomicrographs: 2,000 X. 1-5, *Helicopontosphaera heezenii* n. sp. (1) USNM 176907, DSDP 44.0-4-6, 145-150 cm, 45°, (2) holotype USNM 176908, 45°, (3) holotype, cross-polarized, 0°, (4) USNM 176909, 45°, (5) same as figure 1, cross-polarized 90°. 6-9 *Helicopontosphaera rhomba* n. sp. (6) USNM 176910, DSDP 54.0-2-1, 67-68 cm, 45°, (7) holotype USNM 176911, DSDP 54.0-2-4, 81-82 cm, 45°, (8) holotype, cross-polarized, 90°, (9) same as figure 6, cross-polarized, 90°. 10-12, *Sphenolithus conicus* n. sp. (10) holotype USNM 176912, DSDP 80.5-2, 63-64 cm, 90°, (11) holotype, cross-polarized, 90°, (12) holotype, cross-polarized, 45°.



Size.—13 to 18 microns.

Holotype.—USNM 176908 (Pl. 5, figs. 2-3).

Paratypes.—USNM 176907, 176909.

Type locality.—DSDP 44.0-4-6, 145-150 cm, Horizon Ridge, northwestern Pacific Ocean.

***Helicopontosphaera rhomba* n. sp.**

Pl. 5, figs. 6-9

Description.—This large species has a large elongate central opening that is bridged by a diagonal bar oriented at about 45° to the long axis of the nannofossil. In cross-polarized light, the diagonal bar is bright when the long axis of the nannofossil is aligned with a polarization direction, but it is dark at 45° . The short-axis extinction bands are broad and diffuse when the nannofossil is at 90° . The bar is not in optical continuity with the rim.

Remarks.—*Helicopontosphaera rhomba* is distinguished from *Helicopontosphaera lophota* (Bramlette and Wilcoxon) by its more elongate shape, larger central opening, and more diffuse short-axis extinction bands. It is distinguished from *H. intermedia* (Martini) by its larger, non-sigmoid bar; from *H. parallela* (Bramlette and Wilcoxon) by its more open central area and diagonally aligned bar; and from *H. bramlettei* Müller (= *H. wilcoxonii* Gartner) by its more elongate outline and diagonal (approx. 45°) bar.

Occurrence.—*Helicopontosphaera rhomba* is presently known only from the Philippine Sea in lower middle Miocene deposits cored during DSDP Leg 6.

Size.—15 to 18 microns.

Holotype.—USNM 176911 (Pl. 5, figs. 7-8).

Paratypes.—USNM 176910.

Type locality.—DSDP 54.0-2.4, 81-82 cm, Philippine Sea.

Genus *Sphenolithus* Deflandre, 1952

***Sphenolithus conicus* n. sp.**

Pl. 5, figs. 10-12

Description.—This large species is characterized by its tall triangular outline in side view. The several apical spines are partly coalesced to form the triangular to rounded triangular upper section of the nannofossil. In cross-polarized light, the base is divided into quadrants by the extinction bands when the long axis of the nannofossil is aligned with a polarization direction. The height of the lower quadrants is equal to or slightly greater than the upper quadrants. The apical complex is bright when oriented at 45° to the polarization directions.

Remarks.—*Sphenolithus conicus* could be mistakenly identified as a large *Sphenolithus heteromorphus* Deflandre but is distinguished by the greater proportion of the fossil that is formed by the basal quadrants instead of by the apical complex. It is distinguished from *S. moriformis* (Brönnimann and Stradner) by its triangular instead of hemispheric outline.

Occurrence.—*Sphenolithus conicus* occurs in lower lower Miocene sediment of the lower *Triquetrorhabdulus carinatus* Zone from the Pacific Ocean.

Size.—7 to 12 microns.

Holotype.—USNM 176912 (Pl. 5, figs. 10-12).

Type locality.—DSDP 80-5-2, 63-65 cm, East Pacific Rise, eastern equatorial Pacific Ocean.

***Sphenolithus obtusus* n. sp.**

Pl. 6, figs. 1-9

Description.—This species has a short cycle of small basal spines and a large tapering apical spine constructed of two vertically matched halves. The apical spine halves are flush and terminate together. Seen in side view and cross-polarized light, the contact between the two spine crystallites is planar, because (1) a black median line appears when the median plane of the spine is aligned to a polarization direction, (2) a solid black or white spine appears if a specimen is rolled so that the median plane is parallel to the microscope stage and thus perpendicular to the polarization directions, and (3) oblique orientations produce an off-center black line. In bright field, with a single polarizer, the apical spine is at low relief when aligned to a polarization direction, and the basal cycle is at high relief. When aligned perpendicular to a single polarization direction, the broad base of the apical spine shows a round outline. In cross-polarized light this contributes to the diagnostic obtuse angle made by the extinction line between the apical spine and the basal spine cycle. The basal cycle is short and simple. No side-oriented spines lie between the apical spine and the downward, proximally directed basal cycle.

Remarks.—*Sphenolithus obtusus* is distinguished from *S. furcatolithoides* Locker by the consistent obtuse angle formed between the apical spine and the extinction line between the basal spine in cross-polarized light. *Sphenolithus furcatolithoides* has a single straight extinction line that is perpendicular to the nannofossil axis; it also has divergent halves of the apical spine. *Sphenolithus obtusus* is distinguished from *S. distentus* (Martini) by the three-line extinction pattern of the basal spines, which are also longer than those of *S. distentus*.

In its most typical orientation on prepared slides, *S. obtusus* has the median plane of the apical spine perpendicular to the slide surface. In cross-polarized light at 15° to 25° one whole side of the nannofossil—the base and apical side—is dark. At 45°, the extinction line is missing from the apical spine; instead a light blue line is present that marks the trace of the median plane.

Occurrence.—*Sphenolithus obtusus* is common in upper middle Eocene sediment from Horizon Ridge, northwestern Pacific Ocean. *Sphenolithus furcatolithoides* occurs with *S. obtusus* only in the lower part of the range of *S. obtusus*. This distribution, together with the similarity in construction, suggest the derivation of *S. obtusus* from *S. furcatolithoides*.

Size.—6 to 12 microns.

Holotype.—USNM 176913 (Pl. 6, figs. 1-6).

Paratypes.—USNM 176914-176915.

Type locality.—DSDP 44.0-4-2, 145-150 cm, Horizon Ridge, northwestern Pacific Ocean.

***Sphenolithus spiniger* n. sp.**

Pl. 6, figs. 10-12; Pl. 7, figs. 1-2

Description.—This small species is dominated by a basal ring of spines. In cross-polarized light, the lower basal quadrants are about twice as tall as the upper basal quadrants. The apical structure appears to be a single small spine that is bright at 45° and dark black, when oriented parallel with a polarization direction. When the nannofossil axis is oriented parallel with a polarization direction, the median extinction band is flared near the base of the specimen, giving the large lower quadrants a rounded appearance. At 45° to the polarization directions, the area occupied by the dark flare of 0° or 90° contains two bright spines that form an inverted “v” and that are outlined by black extinction



bands.

Remarks.—*Sphenolithus spiniger* is distinguished from other species of *Sphenolithus* by the unique optical pattern of the basal spines in cross-polarized light and also by the small size and vestigial apical structure. It is distinguished from *S. dissimilis* Bukry and Percival by the triangular outline, the smaller apical structure, and the smaller upper quadrants of the basal structure.

Occurrence.—*Sphenolithus spiniger* is common in upper middle Eocene sediment of Horizon Ridge in the northwestern Pacific Ocean.

Size.—width, 4 to 5 microns; height, 5 to 6 microns.

Holotype.—USNM 176916 (Pl. 6, figs. 10-12).

Paratype.—USNM 176917.

Type locality.—DSDP 44.0-4-6, 145-150 cm, Horizon Ridge, northwestern Pacific Ocean.

***Striatococcolithus* n. gen.**

Description.—These circular and subcircular placoliths are composed of two simple shields connected at the center by a small tube. Each shield is composed of a single cycle of narrow essentially radial elements. In cross-polarized light either both the shields and the small central area are dark to faintly visible, or the shields are dark, but a tiny central area is bright. The lower shield is distinctly smaller than the upper shield.

Type species.—*Striatococcolithus pacificanus* n. sp.

Remarks.—*Striatococcolithus* is distinguished from other genera constructed of two shields and having small simple central areas by the consistent crystallographic alignment of its shield and central area crystallite elements that results in a typical dark appearance of the entire placolith in cross-polarized light. Of the most similar genera, *Cyclococcolithina* Wilcoxon is distinguished by the bright appearance of its smaller shield in cross-polarized light. *Markalius* Bramlette and Martini has strongly inclined and imbricated rim elements and a central area that is consistently bright in cross-polarized light.

***Striatococcolithus pacificanus* n. sp.**

Pl. 7, figs. 3-8

Description.—This circular to subcircular placolith has two distinct shields, each composed of a single cycle of 40 to 60 narrow, radial crystallites. The diameter of the larger shield is 1.6 to 1.7 times that of the smaller shield. The central area is small, occupying only 15 percent or less of the diameter of the larger shield. In cross-polarized light both shields and the central area are typically dark or only faintly visible. A few specimens have a small, vestigial, elliptic, central area that is bright.

Remarks.—*Striatococcolithus pacificanus* differs from other circular to subcircular placoliths by lacking birefringence in both shields and in the central area. The radial crystallites appear as prominent bands extending from the margins to the centers of the shields. Specimens of *S. pacificanus* that have a small bright central area are distinguished from *Markalius inversus* (Deflandre) by their thin, radial, slightly imbricate shield construction.

Plate 6. Photomicrographs: 2,000 X. 1-9. *Sphenolithus obtusus* n. sp. (1) holotype USNM 176913, DSDP 44.0-4-2, 145-150 cm, cross-polarized, 0°, (2) holotype, cross-polarized, 45°, (3) holotype, cross-polarized, 22°, (4) holotype 0°, (5) holotype, 45°, (6) holotype, 90°, (7) USNM 176914, 45°, (8) cross-polarized, 20°, (9) USNM 176915, cross-polarized, 45°, median plane perpendicular to polarization directions. 10-12. *Sphenolithus spiniger* n. sp. (10) holotype USNM 176916, DSDP 44.0-4-6, 145-150 cm, 90°, (11) holotype, cross-polarized, 45°, (12) holotype, cross-polarized, 0°.



Occurrence.—*Striatococcolithus pacificanus* occurs through lower Eocene sediment of the Shatsky Rise in the Pacific Ocean.

Size.—10 to 14 microns.

Holotype.—USNM 176919 (Pl. 7, figs. 4-5).

Paratypes.—USNM 176918, 176920-176921.

Type locality.—DSDP 47.2-7-3, 82-83 cm, Shatsky Rise, northwestern Pacific Ocean.

Genus *Triquetrorhabdulus* Martini, 1965

***Triquetrorhabdulus milowii* n. sp.**

Pl. 7, figs. 9-12

Description.—This small species is constructed of three blades joined symmetrically at a common axis. Oriented in side view, the nannofossil outline, which is formed by two of the blades, is elliptic to rounded rhomboid. In this same orientation, the third blade is seen in edge view. Maximum relief above the mounting medium ($n=1.518$) and maximum birefringence occur at 45° to the polarization directions. In cross-polarized light, the typical color pattern of yellow for the two blades in profile, red for the area next to the third blade (edge view), and blue for the third blade, is a measure of the various thicknesses of the nannofossil at this orientation. Minimum relief and birefringence (dark) for the whole nannofossil is parallel with the polarization directions. Typically the width of the nannofossil is equal to one half or more of the length.

Remarks.—*Triquetrorhabdulus milowii* is distinctly shorter than any other species of *Triquetrorhabdulus*. It is distinguished from *T. inversus* Bukry and Bramlette and *T. rugosus* Bramlette and Wilcoxon by the orientation of the optic axis of the three blades. It is distinguished from *T. carinatus* Martini, with which it shares the same optic-axis pattern, by a shorter more "inflated" profile. *T. milowii* is typically one half or two thirds as wide as long and blade margins tend to be curved, whereas *T. carinatus* is only one third or one fourth as wide as long. Younger specimens of *T. milowii* tend to be shorter and more elliptic in outline than older specimens, with one end slightly wider than the other. This nannofossil has been recorded as *T. carinatus* [short] in Deep Sea Drilling Project reports on the tropical Pacific Ocean. The stratigraphic utility of this species was suggested by Dean Milow (pers. comm., 1969).

Occurrence.—*Triquetrorhabdulus milowii* is common to rare in lower Miocene sediments of the Pacific Ocean and Cipero section of Trinidad. Early forms of *T. milowii* overlap the upper range of *T. carinatus* in the *Triquetrorhabdulus carinatus* Zone, but *T. milowii* persists upward into the *Sphenolithus belemnoides* Zone and possibly into the lower *Helicopontosphaera ampliaperta* Zone, which are above the range of *T. carinatus*.

Size.—6 to 12 microns.

Holotype.—USNM 176922 (Pl. 7, figs. 9 and 12).

Paratype.—USNM 176923.

Type locality.—DSDP 74.0-4-4, 63-64 cm, western flank East Pacific Rise, equatorial Pacific Ocean.

Plate 7. Photomicrographs: 2,000 X. 1-2. *Sphenolithus spiniger* n. sp. (1) USNM 176917, DSDP 44.0-4-6, 145-146 cm, cross-polarized, 45° , (2) cross-polarized, 0° . 3-8. *Striatococcolithus pacificanus* n. sp. (3) USNM 176918, DSDP 47.2-7-2, 100-101 cm, (4) holotype USNM 176919, DSDP 47.2-7-3, 82-83 cm, (5) holotype, cross-polarized, (6) USNM 176920, DSDP 47.2-7-3, 104-105 cm, cross-polarized, (7) USNM 176921, DSDP 47.2-7-3, 82-83 cm, (8) cross-polarized. 9-12. *Triquetrorhabdulus milowii* n. sp. (9) holotype USNM 176922, DSDP 74.0-4-4, 63-64 cm, 45° , (10) USNM 176923, 45° , (11) cross-polarized, 45° , (12) holotype, cross-polarized, 45° .

SAMPLE LOCALITIES

DSDP 3 (23°01'N., 77°43'W.)
 DSDP 36 (40°59'N., 130°07'W.)
 DSDP 44.0 (19°19'N., 169°00'W.)
 DSDP 47.0 (32°27'N., 157°43'E.)
 DSDP 47.2 (32°27'N., 157°43'E.)
 DSDP 54.0 (15°37'N., 140°18'E.)
 DSDP 55.0 (9°18'N., 142°33'E.)
 DSDP 57.2 (8°41'N., 143°32'E.)
 DSDP 63.0 (0°50'N., 147°53'E.)
 DSDP 63.1 (0°50'N., 147°53'E.)
 DSDP 70.0 (6°20'N., 140°22'W.)
 DSDP 72.0 (0°26'N., 138°52'W.)
 DSDP 74.0 (6°14'S., 136°06'W.)
 DSDP 77B (0°29'N., 133°14'W.)
 DSDP 80 (0°58'S., 121°33'W.)
 DSDP 83A (4°03'N., 95°44'W.)
 STETSON 21, (38°58'N., 72°28'W.)

Sample provided by M. N. Bramlette.

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LITERATURE CITED

- Berger, W. H.
 1970. Biogenous deep-sea sediments: Fractionation by deep-sea circulation. *Geol. Soc. America Bull.* 81: 1385-1402.
- Berggren, W. A.
 1971. Tertiary boundaries and correlations. *In*, Funnell, B. M., and W. R. Riedel (eds.) *The micropaleontology of oceans*. Cambridge University Press, p. 693-809.
- Bramlette, M. N.
 1970. Calcareous nannoplankton. *U.S. Geol. Surv. Prof. Paper* 640-A: 18.
- Bramlette, M. N., and E. Martini
 1964. The great change in calcareous nannoplankton fossils between the Maestrichtian and Danian. *Micropaleontology* 10: 291-322.
- Bramlette, M. N., and W. R. Riedel
 1954. Stratigraphic value of discoasters and some other microfossils related to recent coccolithophores. *J. Paleont.* 28: 385-403.
- Bramlette, M. N., and J. A. Wilcoxon
 1967. Middle Tertiary calcareous nannoplankton of the Cipero section, Trinidad, W. I. *Tulane Studies Geol.* 5: 93-131.
- Bukry, D.
 1971. Coccolith stratigraphy Leg 7, Deep Sea Drilling Project. *Deep Sea Drilling Proj. Initial Repts.* 7: 1513-1528.
 Coccolith stratigraphy Leg 16, Deep Sea Drilling Project. *Deep Sea Drilling Proj. Initial Repts.* 16, in press.
- Bukry, D., and M. N. Bramlette
 1970. Coccolith age determinations Leg 3, Deep Sea Drilling Project. *Deep Sea Drilling Proj. Initial Repts.* 3: 589-611.
- Chave, K. E., and E. Suess
 1967. Suspended minerals in seawater. *New York Acad. Sci. Trans.* 29: 991-1000.

- Douglas, R. G.
1971. Cretaceous Foraminifera from the northwestern Pacific Ocean: Leg 6, Deep Sea Drilling Project. Deep Sea Drilling Proj. Initial Repts. 6: 1027-1053.
- Franke, W. W., and R. M. Brown, Jr.
1971. Scale formation in Chrysophyceae algae, III. Negatively stained scales of the coccolithophorid *Hy-menomonas*. Archiv Mikrobiologie 77: 12-19.
- Gartner, S., Jr.
1969. Correlation of Neogene planktonic foraminifer and calcareous nannofossil zones. Gulf Coast Assoc. Geol. Soc. Trans. 19: 585-599.
1971. Calcareous nannofossils from the JOIDES Blake Plateau cores, and revision of Paleogene nannofossil zonation. Tulane Studies Geol. Paleont. 8: 101-121.
- Hay, W. W., H. P. Mohler, P. H. Roth, R. R. Schmidt, and J. E. Boudreaux
1967. Calcareous nannoplankton zonation of the Cenozoic of the Gulf Coast and Caribbean-Antillean area, and transoceanic correlation. Gulf Coast Assoc. Geol. Soc. Trans. 17: 428-480.
- Hulburt, E. M.
1962. Phytoplankton in the southwestern Sargasso Sea and north equatorial current, February 1961. Limnol. Oceanogr. 7: 307-315.
- Hulburt, E. M., and J. Rodman
1963. Distribution of phytoplankton species with respect to salinity between the coast of southern New England and Bermuda. Limnol. Oceanogr. 8: 263-269.
- Lawrence, D. R.
1971. The nature and structure of paleoecology. J. Paleont. 45: 593-607.
- Martini, E., and M. N. Bramlette
1963. Calcareous nannoplankton from the experimental Mohole drilling. J. Paleont. 37: 845-856.
- Martini, E., and T. R. Worsley
1971. Tertiary calcareous nannoplankton from the western equatorial Pacific. Deep Sea Drilling Proj. Initial Repts. 7: 1471-1507.
- Milow, E. D.
1970. Tentative nannofossil zones and subzones and their radiometric age, northeast Pacific. Deep Sea Drilling Proj. Initial Repts. 5: 8-10.
- Peterson, M. N. A.
1966. Calcite: rates of dissolution in a vertical profile in the central Pacific. Science 154: 1542.
- Pytkowicz, R. M.
1969. Chemical solution of calcium carbonate in seawater. Amer. Zool. 9: 673-679.
- Roth, P. H.
1970. Oligocene calcareous nannoplankton biostratigraphy. Eclogae Geol. Helvetiae 63: 799-881.
- Smith, S. V., J. A. Dygas, and K. E. Chave
1968. Distribution of calcium carbonate in pelagic sediments. Mar. Geol. 6: 391-400.
- Tappan, H.
1971. Microplankton, ecological succession and evolution. North Amer. Paleont. Convention Proc. H: 1058-1103.
- Wilcoxon, J. A.
1970. *Cyclcoccolithina* Wilcoxon *nom. nov.* (nom. subst. pro *Cyclcoccolithus* Kampter, 1954). Tulane Studies Geol. Paleont. 8: 82-83.

